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RESEARCH ARTICLE

Revegetated riparian areas are dominated by weeds, and lack structural diversity and natural recruitment: lessons for restoration practice

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Riparian areas can be highly biodiverse and provide critical ecosystem services. However, they are frequently subject to anthropogenic impacts such as land clearing, agricultural use, and urban development. Restoration of riparian areas via revegetation commonly improves the health of waterways and surrounding areas, but vegetation outcomes are rarely assessed. Our study compared 10 to 14-year-old revegetation to remnant vegetation in riparian areas of south-eastern Australia to determine if species composition, vegetation structure, and ecosystem function (plant recruitment) differed. We also assessed if the amount of surrounding native vegetation, browsers (including deer, rabbits, and macropods), or soil characteristics influenced native woody plant recruitment at revegetated sites. While native and exotic woody species richness did not differ, native woody plants were less abundant and exotic woody plants twice as abundant at revegetated sites. The ground layer of revegetated sites was dominated by weeds, whereas remnant sites largely comprised native herbaceous plants and leaf litter. Tree heights and tree canopy cover were similar in revegetated and remnant areas, although shrubs and ferns were lacking in revegetation. Native woody plant recruitment was lower at revegetated sites and was negatively associated with browser presence. Our results suggest that while revegetation may have similar species richness and tree cover as remnant areas, weeds often dominate and important structural components such as shrubs and ferns, and ecological processes such as plant recruitment, are lacking. Better consideration of all vegetation strata, reduced browsing pressure and weed control are likely to achieve better revegetation outcomes.

Key words: animal grazing, exotic species, habitat restoration, target habitat, vegetation, waterways

Implications for Practice

- Tree canopy cover and plant species richness are not sufficient measures on their own for restoration success. Vegetation structure, community composition, and ecological processes are important additional measures for a more holistic picture of restoration outcomes in riparian areas.
- Undertaking riparian revegetation actions near existing remnant areas and managing revegetated areas to reduce browsing pressure and weeds are likely to improve restoration outcomes.
- If appropriate for the vegetation type being restored, the inclusion of shrubs and ferns through infill planting are likely to be beneficial to increase structural diversity in revegetated riparian sites.

and improved water quality (Naiman et al. 1993). However, anthropogenic impacts such as clearing of land for agriculture and urbanization, river regulation, livestock grazing, and the introduction of invasive species have degraded many stream ecosystems to the point of collapse (Palmer et al. 2005; Wohl et al. 2015).

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Introduction

The health and functioning of rivers depend on intact riparian vegetation (Singh et al. 2021). Riparian areas generally support distinct and more structurally complex vegetation than non-riparian areas, and are relatively biodiverse (Naiman et al. 1993; Munro et al. 2009b). Riparian vegetation also provides ecosystem services including through bank stabilization

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Ecological restoration is commonly undertaken to repair degraded ecosystems with the aim of facilitating the recovery of biodiversity and ecological function, ideally to a similar state they were in before they were degraded, damaged, or destroyed (Benayas et al. 2009). Riparian restoration most commonly involves fencing off riparian areas from livestock, managing browsing pressure and weeds and replanting native vegetation or allowing native species to recruit naturally (Brooks & Lake 2007). The substantial investment made annually by government and nongovernment agencies and community groups in restoration, including revegetation, is predicated on the assumption of assisting the recovery of sites to a more natural state, depending on the goals of the project (Ruiz-Jaen & Aide 2005). However, lack of funding for evaluation generally means that monitoring and assessment of restoration effectiveness is generally lacking (Benayas et al. 2009; González et al. 2015).

Natural plant recruitment within restored areas is essential to ensure that these areas are self-sustaining and resilient in the long term (Ruiz-Jaen & Aide 2005). Ideally it would be more cost-effective and arguably provide better conservation outcomes if cleared landscapes restored themselves through natural recruitment. However, passive restoration through natural recruitment seldom occurs, particularly in heavily disturbed landscapes (Pardos et al. 2005; Sieben & Reinecke 2008; Vesik et al. 2008). Recruitment is known to be limited by several factors including competition from weed species, reduced dispersal opportunities in fragmented landscapes, browsing pressure and abiotic factors such as soil characteristics (Elgar et al. 2014; Moser & Greet 2018). In revegetated areas, natural recruitment may also be limited by the density of the plantings, with very dense plantings reducing the subsequent recruitment of native plants (McCallum et al. 2018).

The Society for Ecological Restoration (SER) provides guidelines to effectively monitor and assess the outcomes of restoration actions, according to six key attributes that restored environments should have (Gann et al. 2019). These attributes are: species composition, structural diversity, ecosystem function, external exchanges, absence of threats, and physical condition. To monitor restored areas effectively, the guidelines suggest the use of a “recovery wheel” to indicate the level of change in the six key attributes, and suggest that restored areas need to be compared with reference sites of a similar vegetation type that have not been degraded (Gann et al. 2019). However, restoring areas so they reflect undisturbed sites may be difficult or impossible if areas undergoing restoration have been impacted by major hydrological and geomorphic changes such as river regulation and changed hydrological regimes, channel erosion and incision, and floodplain disconnection (Reich & Lake 2015).

Furthermore, land managers may not necessarily aim to fully restore areas targeted for management, rather aiming to restore only aspects of a site’s vegetation. Even reference sites may not be truly representative of previous environments due to changes in the surrounding landscape, invasion by non-native plant and animal species, and a homogenization of species compositions and ecological processes (Alberti 2005). Climate change is likely to increasingly impact both revegetated and remnant areas, making revegetation outcomes more

uncertain (Jellinek et al. 2020). However, comparing restored areas to paired remnant sites is still recognized as being important to track how flora and fauna changes over time (Gann et al. 2019; Bennett et al. 2022).

Here, we present research on the effectiveness of forest restoration along waterways in southeast Victoria, Australia. Assessing aspects from the six SER recovery wheel attributes, we compare 10- to 14-year-old revegetation to remnant (reference) vegetation to ask if (1) *species composition* in terms of the species richness and abundance of native and exotic woody plants, and cover of ground layer vegetation; (2) vegetation *structural diversity*; and (3) *ecosystem function* (plant recruitment) differ between these areas. We also assess how native woody plant recruitment at revegetated sites is influenced by (4) *external exchanges* (surrounding native vegetation), (5) *absence of threats* (browser presence), and (6) *physical conditions* (soil nutrients and bulk density). We then consider the implications of our findings for land managers seeking to more effectively restore riparian vegetation.

Methods

Study Sites

This study was undertaken in the greater Melbourne area in Victoria, Australia (Fig. 1). We selected 17 riparian sites at which restoration activities had been undertaken by regional waterway manager Melbourne Water between 2010 and 2014 across several catchments. Restoration generally included revegetation of native trees, shrubs, grasses and other understorey plants, woody and herbaceous weed control, and fencing out of livestock (hereafter “revegetated” sites). Unfortunately, data on the species mixes used, planting densities, and maintenance regimes for these sites were patchy and incomplete. We also lacked detailed records on the specific goals of the restoration plantings, beyond the overarching goal of increasing native species richness and vegetation structure at the revegetated sites.

Sites were located on private land or public land. We paired revegetation sites with nearby remnant vegetation as exemplars of relatively intact mature native vegetation characteristic of the local landscape (hereafter “remnant” sites). Sites were paired based on predicted Ecological Vegetation Class (EVC—DEECA 2022) via desktop analysis, and then assessed on-ground to ensure the site characteristics and vegetation types were similar (Table S1). Site EVC groupings were dominated by riparian scrubs, but also included wet forest, dry forest, and riverine grassy woodland. Paired sites were mostly of the same EVC grouping. All sites were adjacent to low to mid-land perennial streams ranging in elevation from 1 to 539 m. Specific site vegetation community and stream details are provided in Table S1.

It is important to note that Melbourne Water did not undertake riparian revegetation with a goal of attaining the full suite of attributes of remnant vegetation. We opted to use paired remnant sites because we consider them to be valuable points of comparison for improving restoration practice in human-modified

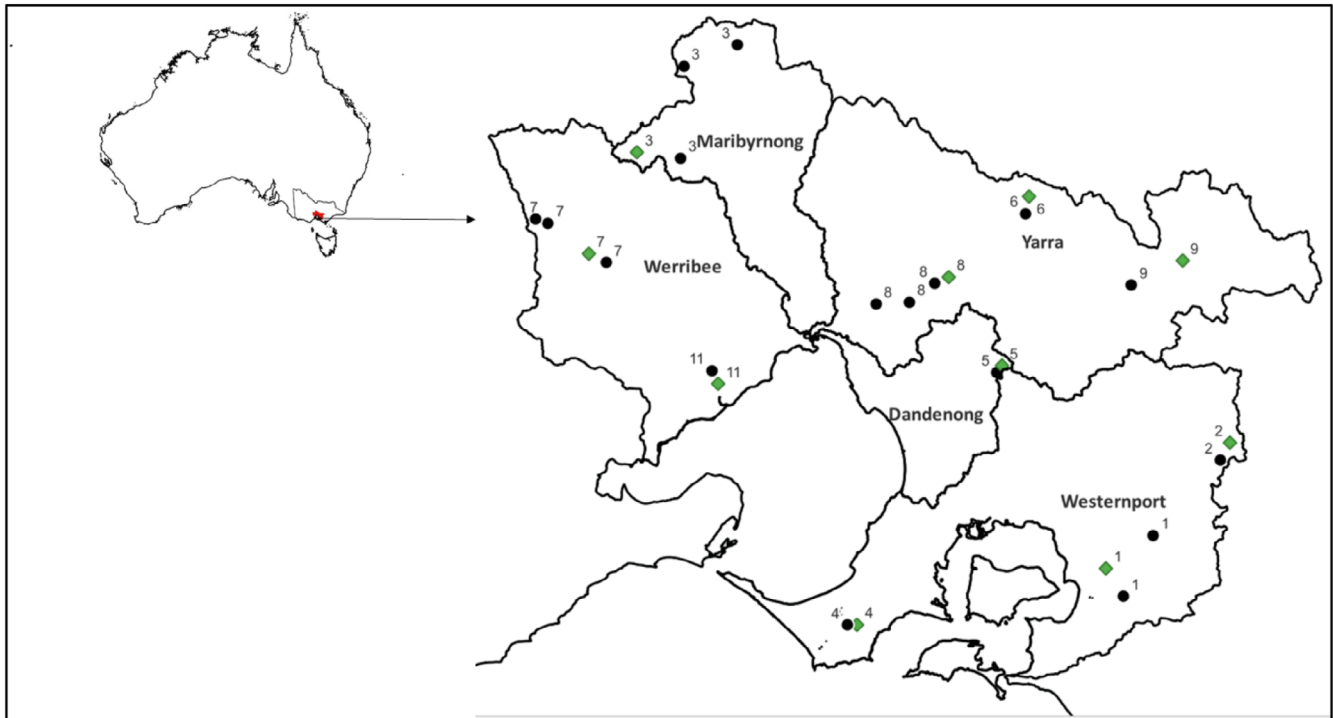


Figure 1. Survey sites in the greater Melbourne area, including Catchment areas. Black dots represent revegetated sites while green diamonds represent target remnant sites. Numbers indicate site pairings.

landscapes. Due to the lack of appropriate remnant vegetation, some remnant sites were paired with more than one revegetated site with similar vegetation types. In total, we assessed 27 sites comprising of 17 revegetated sites and 10 remnant sites (Fig. 1).

Field Surveys

Sites were assessed in the winter (May–August 2021) and spring months (September–November 2021). Restrictions resulting from Covid-19 caused the field surveys to be spread over two seasons.

We assessed vegetation composition and structure at revegetated and remnant sites using a method specifically designed to monitor management interventions such as revegetation; the Restoration Outcomes Monitoring Protocol (ROMP). The ROMP method is informed by the SER guidelines and designed to assess the effectiveness of management interventions including revegetation and weed control and to track vegetation changes at restored sites (Jellinek et al. 2022). The ROMP was used to assess the vegetation composition and structure at each site within a 250 m stream reach. For detailed guidelines of the ROMP method see Jellinek et al. (2022).

Firstly, six 20 m × 4 m belt transects were established at each site (Fig. 2). The six belt transects were at least 30 m apart from one another within the 250 m reach. Steep or eroding banks were avoided, in which case another location was chosen. At each transect location, a 20 m tape measure was laid perpendicular to the stream, with 0 m starting at the wetted edge of the stream (Fig. 2). All surveys were conducted during low to

moderate flow conditions (no flooding was occurring). This meant that each belt transect encompassed a range of hydrological niches from frequently to infrequently flooded landforms and that a representative sample of vegetation across the active riparian zone at each site was surveyed.

For each belt transect, all tree and shrub species were identified, and the numbers of individuals rooted within the transect for each species tallied. For each tree and shrub species, up to five plants had their heights recorded along the length of the transect. Woody plant recruits were identified to species level and tallied. Recruits were identified as tree or shrub saplings less than 1 m tall that had not reached sexual maturity (had not yet flowered) (Table S2).

To assess ground layer vegetation and attributes, we surveyed thirty 1 m × 1 m quadrats at each site. Five 1 m × 1 m quadrats were established along each of the six belt transects, at 0 m and then at every 5 m thereafter. Quadrats were placed on the upstream side of the belt transect (Fig. 2). Within each quadrat, the percentage cover of native ground cover, exotic ground cover, leaf litter/fine woody debris (width <10 cm diameter), coarse woody debris (>10 cm diameter), bare ground, rock, or water was visually estimated to the nearest 5%. As different ground cover types can overlap each other, the summed total of these estimates could total over 100%. Also, within each quadrat the presence of any pellets of browsing animal species were recorded and the browser pellets identified as kangaroo, wallaby, deer, rabbit, or other.

We used a 2 m structure pole to determine the vegetation structure of different plant forms at each site. Vegetation structure was assessed by placing the structure pole vertical to the

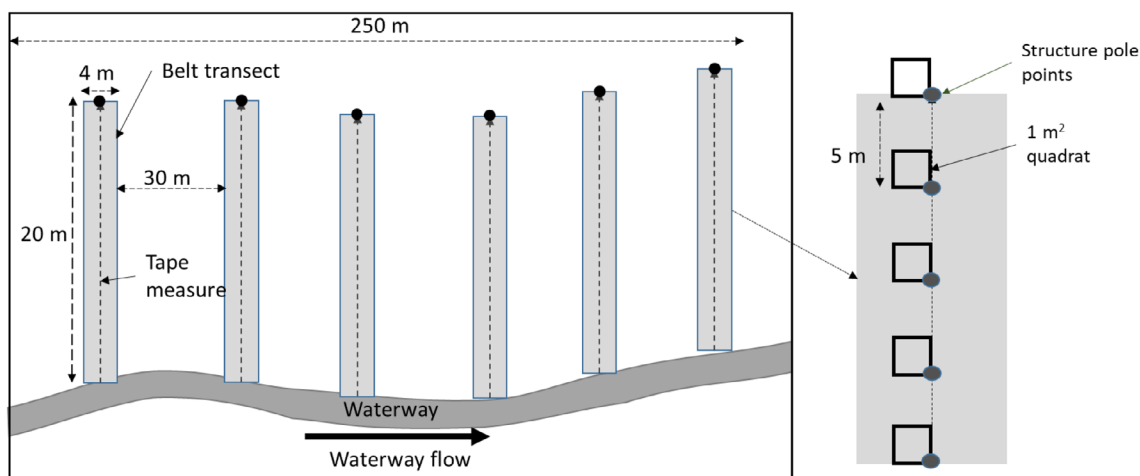


Figure 2. Diagram of the ROMP survey design undertaken at revegetated and remnant sites. Not to scale.

ground along the mid-transect line every 5 m (i.e. at 0, 5, 10, 15, and 20 m; see Fig. 2). The pole was marked to identify different height classes (0–0.5, >0.5–1, >1–1.5, and >1.5–2 m). For each height class we recorded plants touching the pole categorized in the following plant forms: tree, shrub, herbaceous, or fern. We assessed canopy cover by looking up along the line of the vertical structure pole to see if the pole would continue up through the bounds of a tree crown. If so, canopy was recorded as present (P), if not it was recorded as absent (A). Canopy cover was defined as any tree species that was greater than 10 m tall and had a canopy that overhung the area being surveyed.

Soil Sampling

At each site, three soil samples were collected for assessment of soil bulk density and another three samples collected for soil chemistry analysis. One sample for each was collected from the ends of each of three random belt transects. The bulk density samples were collected by hammering a metal ring (volume = 278.3 cm³) into the ground and collecting the soil. The chemical analysis samples were collected by taking a 10 cm deep, 5 cm diameter core of topsoil. The samples were then placed in a drying oven at 40°C for 4 days. Soil bulk density was calculated as the dry weight of soil divided by its volume. Chemical analysis for total nitrogen and total phosphorus was undertaken at external laboratories using standard protocols.

Spatial Analyses

The proportion of the area surrounding each site that was native vegetation was calculated from spatial data using the Native Vegetation Extent (2017) layer for Victoria (DEECA 2022). This was done by calculating the percentage of native vegetation within an area of 500 m radius around each survey site centerpoint.

Data Analyses

For native and exotic woody plant abundance, and abundance of native woody recruits, we first converted stem counts (per belt transect) to a density measure (stems/ha) by dividing counts by the surveyed area (i.e. 20 m × 4 m = 80 m²) and multiplying by 10,000. These abundance values were then averaged at the site level and rounded to the nearest whole number.

For analyses of native and exotic woody species richness and plant abundance, and abundance of native woody recruits, we used Poisson regression with abundances modeled as a function of site type (revegetated or remnant) with site pair included as a random factor to account for the deliberate spatial pairing of revegetated and remnant sites.

Plant heights were only considered for species for which *at least* three individuals occurred within *at least* three sites (to avoid one or two plants at a given site having undue influence on the analyses, and to allow for comparison across site types). Using individual plant data for those species, we modeled plant height as function of site type, species, and their interaction, and included site, nested within site pair as random factors. For this model, we were interested in the interaction term, that is, the differences in plant heights within species between site types.

When analyzing ground layer cover data, we used beta regression with all cover variables first scaled to between 0 and 1. Using the quadrat level data, we modeled cover as a function of site type (revegetated or remnant), with site nested within site pair included as random factors.

For analyses of the vegetation structure data, we also used a beta regression. Firstly, the frequency of “hits” of the different plant life forms within the different height classes, and canopy presence, were expressed as a proportion (between 0 and 1) at the site level. For analyses of the different life forms, we modeled frequency of “hits” as a function of site type (revegetated or remnant), height class (0–0.5 m, >0.5–1 m, >1–1.5 m, >1.5–2 m), and their interaction, and included site pair as a

random factor. For analyses of canopy “hits,” models included site type as the sole fixed effect and site pair as a random effect.

To assess potential drivers of native woody plant recruitment at revegetated sites, we used a Poisson regression with the abundance of native woody plants (stems/ha) modeled as a function of either: proportion of surrounding landscape comprising native vegetation, browser pellet frequency, soil nutrients (total nitrogen or total phosphorous), or soil bulk density (using single predictor models in each case). For each of these models, we calculated the deviance explained (r^2) using the formula: $1 - \text{deviance}/\text{null deviance}$. We only considered single predictor models, and not multivariate models, due our limited number of sites ($n = 17$ revegetated sites). For browser pellet frequency, we summed the frequencies of pellets for all browser species recorded at each site. Data for soil nutrients and bulk density were firstly averaged at the site level.

For data illustration, we provide raw means in text and present boxplots (for abundance data) or bar plots (for proportional data) of means and standard errors at the site-level. The statistical software R (R Core Team 2018) and the *glmmTMB* package (Brooks et al. 2023) were used for all analyses.

Results

Species Composition: Native and Exotic Woody Plants

Across the 17 revegetated and 10 remnant sites, 77 woody plant species were recorded including similar numbers of native (49 vs. 46) and exotic (13 vs. 9) woody plant species at the two site types (see Table S2). At the site level, revegetated sites had, on average, similar numbers of native species (mean = 9.9 vs. 11.6; $p = 0.236$) but around two-thirds the native woody stem density (1350 vs. 2181 stems/ha; $p < 0.001$) compared to remnant sites (Fig. 3A & 3B).

Both revegetated and remnant sites had, on average, comparable and relatively few numbers of exotic woody plant species (1.6 vs. 0.9; $p = 0.146$), but revegetated sites had, on average, almost twice the exotic woody stem density (129 vs. 81 stems/ha; $p < 0.001$) than remnant sites (Fig. 3D & 3E).

Species Composition: Ground Layer Vegetation

The ground layer of revegetated sites was dominated by exotic herbaceous plants (mean = 58% cover), whereas the ground

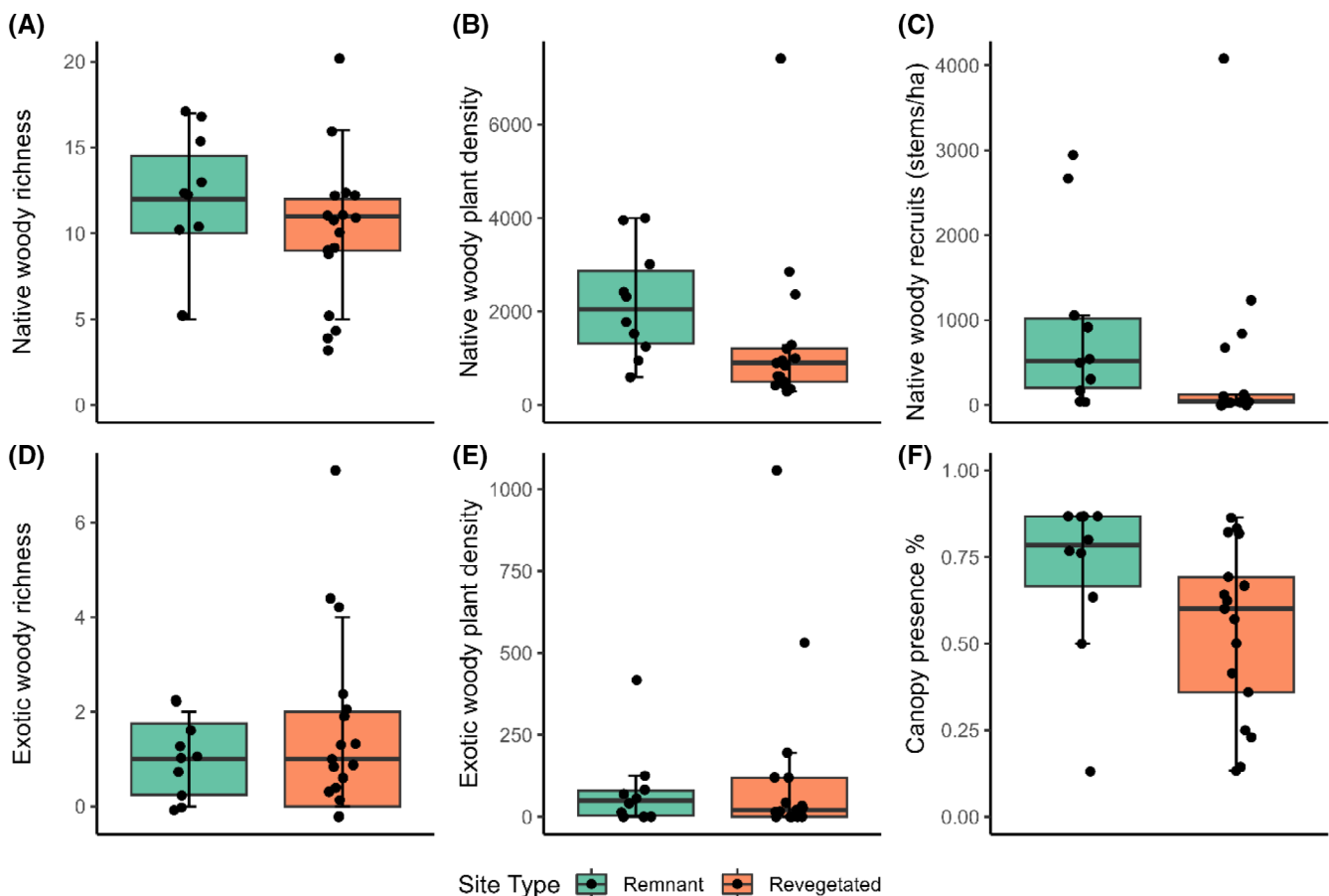


Figure 3. For remnant (green, $n = 10$) and revegetated (orange, $n = 17$) sites, the top row shows boxplots of native woody tree and shrub (A) species richness, (B) density (stems/ha), and (C) recruitment. The bottom row shows boxplots of exotic woody tree and shrub (D) species richness and (E) density (stems/ha), along with (F) tree canopy presence.

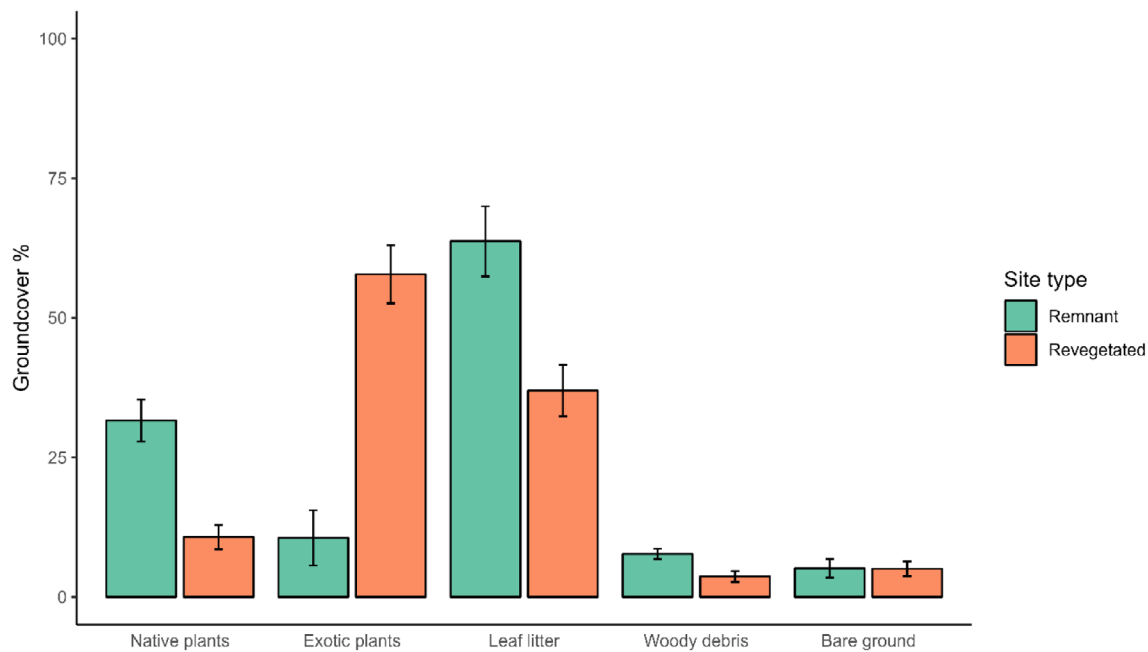


Figure 4. Ground layer vegetation and attributes at remnant (green, $n = 10$) and revegetated (orange, $n = 17$) sites (bar plots indicate raw means \pm SE).

layer of remnant sites predominantly comprised leaf litter (64%) and native herbaceous plants (32%) (Fig. 4). Revegetated sites had greater exotic herbaceous plant cover than remnant sites (58 vs. 11%; $p < 0.001$), whereas remnant sites had a greater cover of litter (64 vs. 37%; $p < 0.001$), native herbaceous plants (32 vs. 11%; $p < 0.001$), and coarse woody debris (8 vs. 4%; $p < 0.001$). The cover of bare ground was similar at both site types (approximately 5%; $p = 0.97$).

Structural Diversity: Vegetation Structure

Some aspects of the vegetation structure differed markedly between revegetated and remnant sites (Fig. 5). Shrubs were recorded more than twice as frequently at remnant sites than revegetated sites (0.17 vs. 0.07; $p < 0.001$) across all height classes. Ferns were recorded much more frequently at remnant sites than revegetated sites (0.16 vs. 0.01; $p < 0.001$), particularly at lower height classes. Both trees and herbs were similarly prevalent at revegetated and remnant sites (Fig. 5; $p > 0.05$).

The frequency of canopy “hits” was, on average, greater at remnant sites than revegetated sites (0.71 vs. 0.54), but there was no clear difference in canopy cover between site types ($p = 0.103$; Fig. 3F).

For the 18 species suitable for comparison (see Section 2), most did not differ in plant height between revegetated and remnant sites; only four did. Of those species, two shrubs *Coprosma quadrifida* and *Goodenia ovata*, and the invasive exotic tree *Pittosporum undulatum* were taller at revegetated sites, whereas only one native tree species, *Eucalyptus cypello-carpa*, was taller at remnant sites (Fig. S1).

Ecosystem Function: Native Woody Plant Recruitment and Its Potential Drivers

The amount of native woody plant recruitment at revegetated sites was around half that at remnant sites (434 vs. 918 stems/ha; $p < 0.001$) (Fig. 3C).

Associations between potential drivers of native woody plant recruitment were generally poor with the exception of browser pellet frequency (Fig. 6). The recruitment of native woody plants at revegetated sites was negatively associated with increasing browser pellet frequency ($p < 0.001$; $r^2 = 0.25$) with recruitment typically negligible where browser pellet frequency was greater than 0.03 (i.e. pellets present in 2 or more of the 30 quadrats at a site; Fig. 6B). There also tended to be greater native woody plant recruitment where total nitrogen levels in the soil were higher ($p < 0.001$, $r^2 = 0.10$; Fig. 6D), whereas relationships between native woody plant recruitment and the percentage of native vegetation in the surrounding landscape, soil compaction (bulk density), or total phosphorous were poor ($r^2 < 0.05$).

Discussion

Our results revealed that 10- to 14-year-old revegetated forest along waterways had similar species richness to remnant areas. However, revegetated areas had lower native woody plant density, twice the density of woody weeds, and a ground layer dominated by weeds with a lower cover of native plants and leaf litter than remnant areas. Structurally, revegetated areas had a similar prevalence of trees and tree cover to remnant areas, but shrubs and ferns were lacking. Finally, native woody plant recruitment at revegetated sites was lower than at

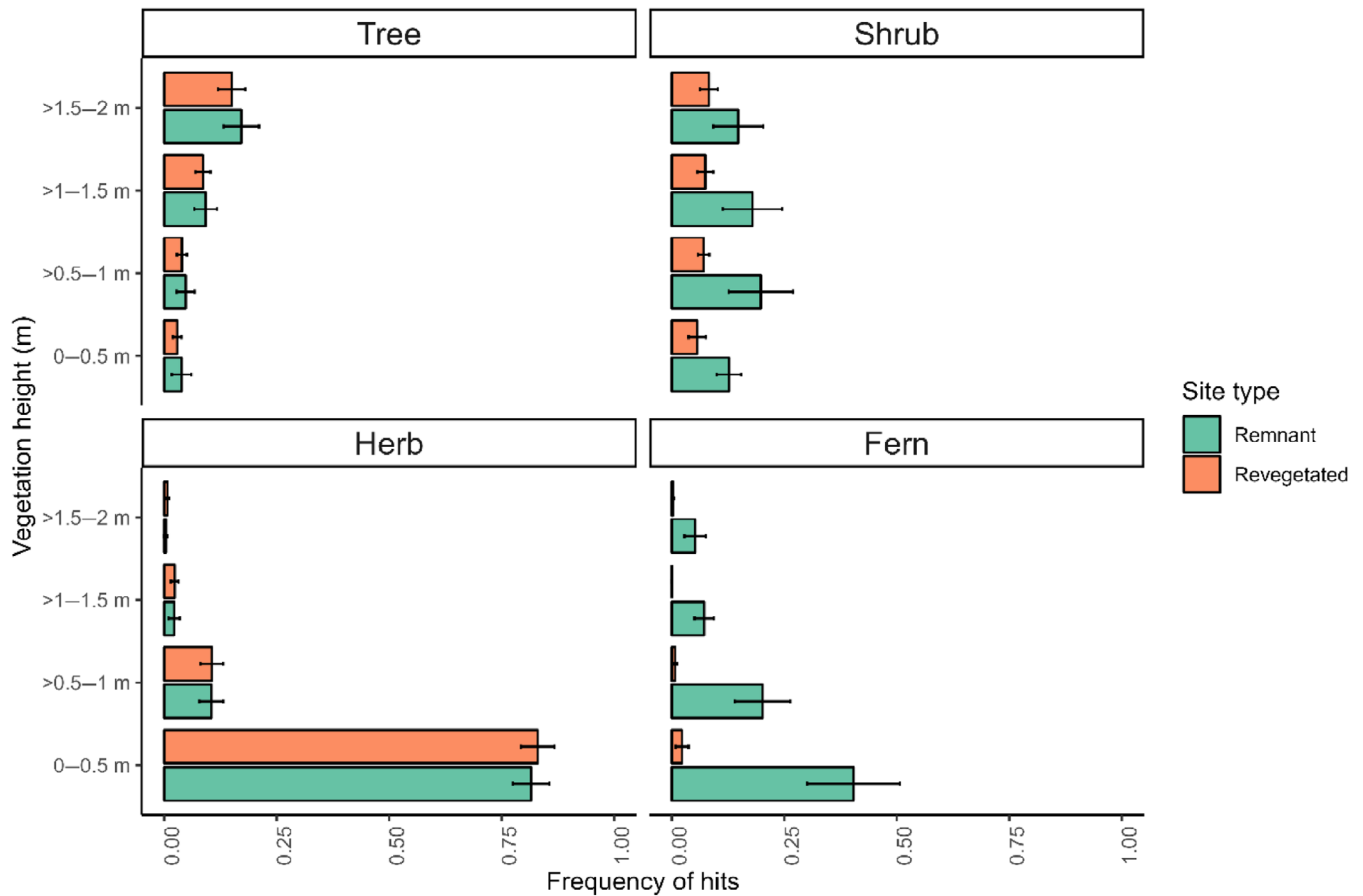


Figure 5. Vegetation structure (tree, shrub, herb, and fern frequency) for different height classes at remnant (green, $n = 10$) and revegetated (orange, $n = 17$) sites (bar plots indicate raw means \pm SE).

remnant areas and was limited by browser prevalence in particular. Our findings indicate that the broad restoration goals of increased native vegetation species richness and cover were met at the revegetation sites. However, they also point to additional important attributes that should be taken into account in restoration practice if we wish to achieve lower weed loads, more structurally diverse and reproductively self-sustaining restored vegetation.

Species Composition

Revegetated sites had similar numbers of native woody plant species to remnant areas in our study, but lower native woody plant density, higher exotic woody plant density, and a ground layer dominated by exotic plant species. A comparable study at 57 sites across south-eastern Australia similarly found that while tree species richness were similar in revegetated and remnant areas, revegetated areas had fewer shrub species (Wevill & Florentine 2014). Likewise, a study of revegetation in agricultural areas concluded that species richness and floristic diversity, particularly of native understorey plants, was lower in restoration plantings than in remnant vegetation (Munro et al. 2009b). More broadly, global meta-analyses of outcomes of forest restoration (including but not limited

to revegetation) suggest that biodiversity is typically enhanced by restoration but remains lower in restored than reference ecosystems (Benayas et al. 2009).

The higher densities and cover of exotic plant species at our revegetated sites are likely to have negatively influenced the prevalence of native plants at these sites. Invasion by exotic plants in natural ecosystems is a well-recognized threat to global biodiversity and a pervasive problem in restoration practice (González et al. 2015). Weeds are highly adaptable and able to establish quickly in disturbed riparian areas (Richardson et al. 2007), potentially greatly reducing the abundance, diversity, recruitment, and survival of native plant species (Burgman et al. 2007; Reid et al. 2009; McAlpine et al. 2017). As many of our revegetation sites were in areas previously disturbed by agricultural and urban activities, their conditions are likely to be conducive to weed invasion and inherently difficult to restore (Crouzeilles et al. 2016).

Structural Diversity

In our study, revegetated sites had much lower shrub and fern density than remnant sites after 10–14 years. Other studies have also shown that shrubs, especially smaller shrub species, are generally lacking in revegetated areas (Wevill & Florentine 2014).

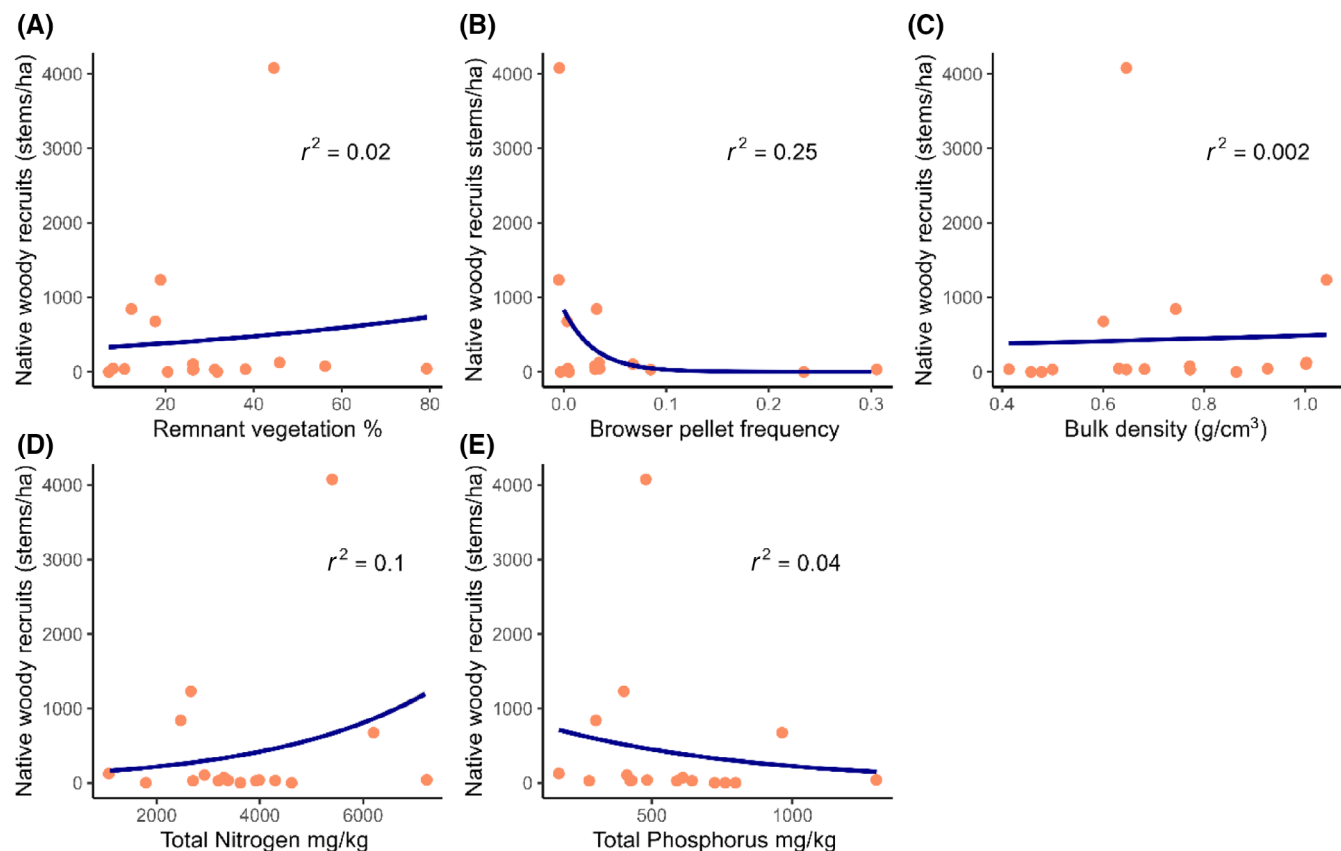


Figure 6. Relationships between potential drivers of restoration success and native woody plant recruitment at revegetated sites ($n = 17$). Linear regression line provided where relationship was significant ($p < 0.05$) and r^2 values provided for all relationships.

This is probably because smaller shrubs and ground layer plants were seldom planted in older (10+ years) revegetation projects. However, a study by Suganuma and Durigan (2015) on Brazilian Atlantic Forest found time to reach reference condition was generally faster for structural attributes than for components such as species composition and functional traits. This is supported by Munro et al. (2009b) who showed that structural complexity in revegetated forests reflected that in remnant vegetation for sites greater than 26 years old, but floristics did not. Therefore, it may take substantially longer for the revegetated areas that we studied to develop similar structural diversity to comparable remnant areas. While ferns were lacking from many of the revegetated sites we assessed compared to remnant areas, this is likely due to these species not being included in the initial planting mixes, rather than them dying post-planting (Munro et al. 2009b).

Interestingly, canopy cover was not substantially different between revegetated and remnant sites in our study, and this is supported by literature which suggests that canopy development may be fairly rapid in restored sites and not a key attribute of restoration success (Crouzeilles et al. 2016). Likewise, plant heights did not differ substantially between revegetated and remnant sites and may rather be limited by abiotic (e.g. climatic and soil type) and biotic factors (Greet et al. 2020).

Ecosystem Function

Woody plant recruitment was substantially lower at our revegetated than remnant sites indicating a potential lack of resilience or regeneration capacity in the planted communities that we studied. Wevill and Florentine (2014) similarly found that native plant recruitment at revegetation sites up to 12 years old were substantially lower than at remnant sites and attributed this to higher weed densities. Natural recruitment is often lacking in revegetated areas (Ammond et al. 2013) but may improve with time since planting (Wevill & Florentine 2014). At our sites, natural recruitment may be constrained by a range of factors, including site age, dense weedy understorey, landscape fragmentation, soil type, and microbial diversity (Deng et al. 2018), lack of structural attributes such as ferns and shrubs (George & Bazzaz 1999) and browsing by native and introduced animals.

Constraints to Natural Recruitment

Plantings that are undertaken closer to existing native vegetation generally have better biodiversity outcomes than those that are more isolated from remnant areas (Thomson et al. 2009). Our study supports this, as we found that greater surrounding native vegetation was positively associated with

native plant recruitment, maybe as a result of increased availability of seed sources and pollinators from nearby remnant vegetation. In a study of the Brazilian Atlantic Forest, Crouzeilles et al. (2020) found that forest proximity was the most important predictor of natural regeneration occurring, and that 90% of natural regeneration occurred less than 200 m from forested areas. Other studies have also shown that restoration plantings are most effective when they are undertaken in mixed landscape areas where remnant areas are present (Bennett et al. 2022).

We found good evidence that high browsing pressure limits native woody plant recruitment at revegetated sites. Studies of browser diets and effects on recruitment show both exotic and native browsers (comprising introduced rabbits and deer and native macropods, in our study) may preferentially consume native seedlings over exotic vegetation, thereby reducing native plant recruitment (Davis et al. 2008; Munro et al. 2009a). Nonetheless, assessment of the respective impact of different browser species or introduced vis-à-vis native browsers on recruitment was not possible with our dataset and further investigation of their relative impact on revegetation is required. The combined effects of high browsing pressure and high weed loads at revegetated sites may also help to explain differences in structural and understorey attributes at revegetated compared to remnant sites.

Soil nutrients such as nitrogen and phosphorus are known to benefit the growth and survival of restored plant populations (Freitas et al. 2019; Klein-Raufhake et al. 2022). Our study similarly found that higher nitrogen levels were correlated with higher native woody plant recruitment, potentially because increased soil nutrients promote plant establishment and growth. However, we found no support for a role of phosphorus in higher levels of plant recruitment. A study by Hacker et al. (2011) in south-eastern Australia similarly showed that phosphorus addition did not benefit plant productivity in grassland ecosystems, but that vegetation dynamics were driven largely by nitrogen.

Lessons for Restoration Practice

It is important to acknowledge that there are several of limitations to this study. We lacked data on specific goals of the restoration plantings, the species mixes used, planting densities, and maintenance regimes at the revegetation sites. This meant we could not assess the outcomes based on what species were initially planted, the density of these plantings, the site preparation, and site management that was undertaken prior to and directly after planting, or detailed restoration goals beyond increasing native species richness and vegetation cover. For example, it is unlikely that many species of ferns or small shrubs were initially planted as they can be difficult to propagate and obtain planting stock for, and it may have been thought that these species would naturally recolonise an area, based on the “Field of Dreams” hypothesis—“if you build it, they will come.” (Palmer et al. 1997). This uncertainty highlights the need for good documentation of restoration projects, and having a database that is designed to store information such as restoration goals, species mixes, planting densities and timing, and site

preparation, and maintenance records. Our surveys were also only conducted at one time period with a limited sample size, so without repeat surveys across more sites and at multiple years it is difficult to determine the extent of influence of threats such as browsing pressure or weed densities.

Nonetheless, our study highlights that there are substantial differences in species composition, vegetation structure, and ecological processes (natural recruitment) between 10- and 14-year-old revegetation and respective remnant vegetation. Importantly, these results demonstrate the value of monitoring restored vegetation, and using remnant areas as benchmarks for the assessment of restoration outcomes. Though remnant areas change over time as a result of natural disturbance impacts such as fires and floods, invasion by pest plants and animals, as well as with climate change, they are nonetheless useful for understanding changes at restored sites (Bennett et al. 2022).

While native plant species richness in revegetated habitats is often used as a measure of restoration success, other measures such as species and functional composition have been shown to be more useful (Laughlin et al. 2017). Therefore, assessments of restoration outcomes may be more valuable for land managers if evaluated against community composition and trait-based measures rather than species richness and abundance. Similarly, restoration goals that are explicit and aim to compare revegetated areas to remnants with the same vegetation type and structure are important aspirations for future restoration programs.

Vegetation structure differed markedly between revegetated and remnant areas, with the former particularly lacking in shrubs and ferns, suggesting that the inclusion of a broader range of structural components (e.g. trees, tall and small shrubs, ferns, ground cover plants, etc., as appropriate) when planting is advisable. While some of these components may develop with time post-planting, or be unsuitable given the vegetation type being restored, management activities such as infill planting of native shrubs and ferns may be useful to support this trajectory, particularly for past revegetation sites lacking these elements. Similarly, a greater understanding of the role of soil type and microbial diversity may improve restoration outcomes (Deng et al. 2018). Predictions of a warming and drying climate give impetus to these management actions, as shrub density and canopy cover are predicted to decrease over time as a result of climate change in south-eastern Australia (Bennett et al. 2013; Jellinek et al. 2020).

Time since restoration and previous land use history are known to be key drivers of restoration success, with restored areas that are older and undertaken on less disturbed land (such as partially cleared areas) likely to resemble reference areas more readily than younger plantings and plantings in more highly disturbed landscapes (Vesk & Mac Nally 2006; Crouzeilles et al. 2016). This suggests that planting on sites that have less of an agricultural legacy may be more effectively restored than sites that have had a long history of agricultural or urban impacts.

Measuring ecological processes such as natural recruitment is important because it indicates the resilience of a restored ecosystem (Ruiz-Jaen & Aide 2005). To promote

natural recruitment and the resilience of revegetated areas, a range of management actions may be required. Revegetation in more fragmented and isolated areas may require more time and effort but can still be important for conservation outcomes at the landscape scale (Bennett et al. 2022). Protecting revegetated areas with fencing and/or ensuring invasive or overabundant native browsers and weeds are effectively controlled is likely to be necessary to allow the space and time for seedling recruitment and for restored ecosystems to become more resilient.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Summary characteristics of the study sites.

Table S2. List of woody plant species recorded within belt transects at remnant ($n = 10$) and revegetated sites ($n = 17$) and the number of sites at which they were recorded for the respective site types.

Figure S1. The average height of plant species present at remnant (green) and revegetated (orange) sites.

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